



Accelerators to make Electricity– An Overview of Heavy-Ion-Driven Fusion

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Talk Outline

Fusion for Commercial Energy Production

- Advantages of fusion
- How do you do it?
- Why use an accelerator?
- What does the system look like?

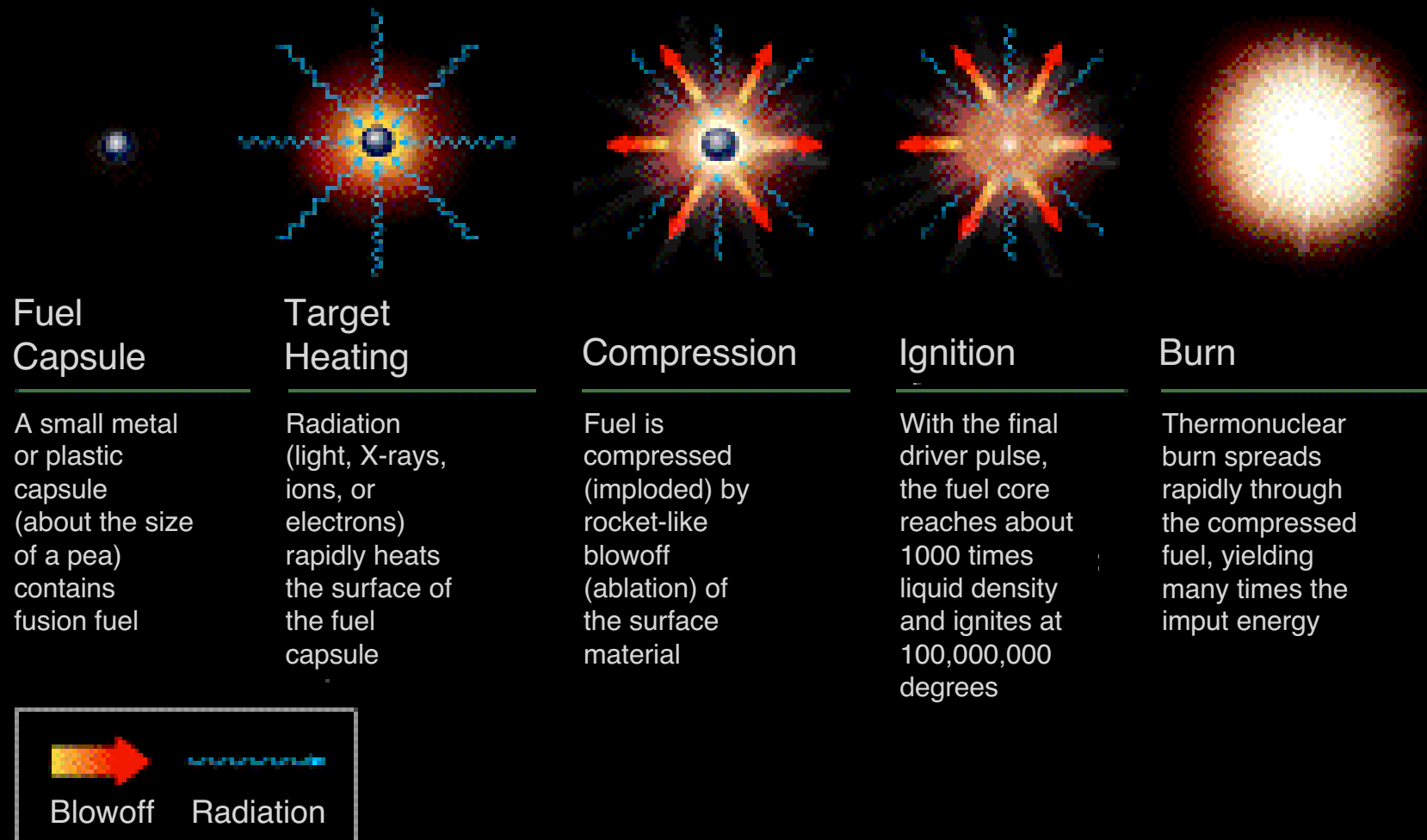
What Physics Do We Do?

- How and why we use computers
- An example

Where are we, and where are we going?

- Status & plans

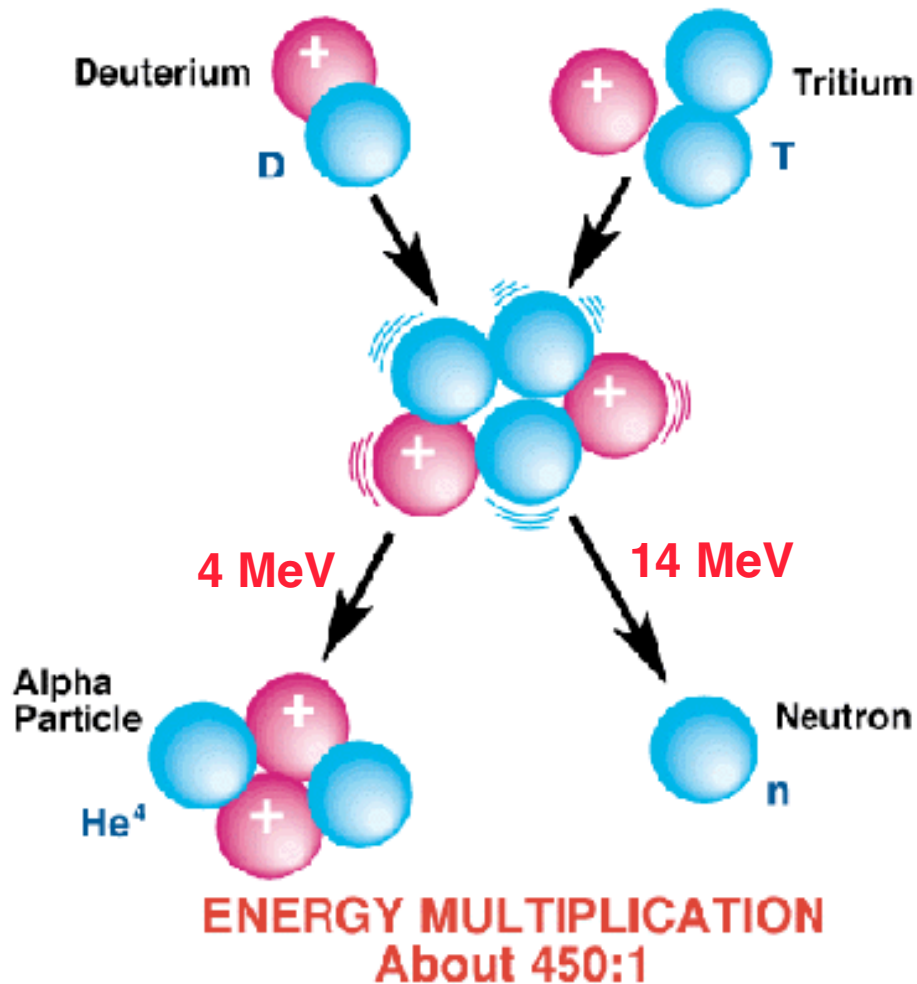
Inertial Confinement Fusion Concept





Fusion is an attractive energy source

Deuterium–Tritium Fusion Reaction



Plentiful fuel

No radioactive waste
from reaction

No chain reaction

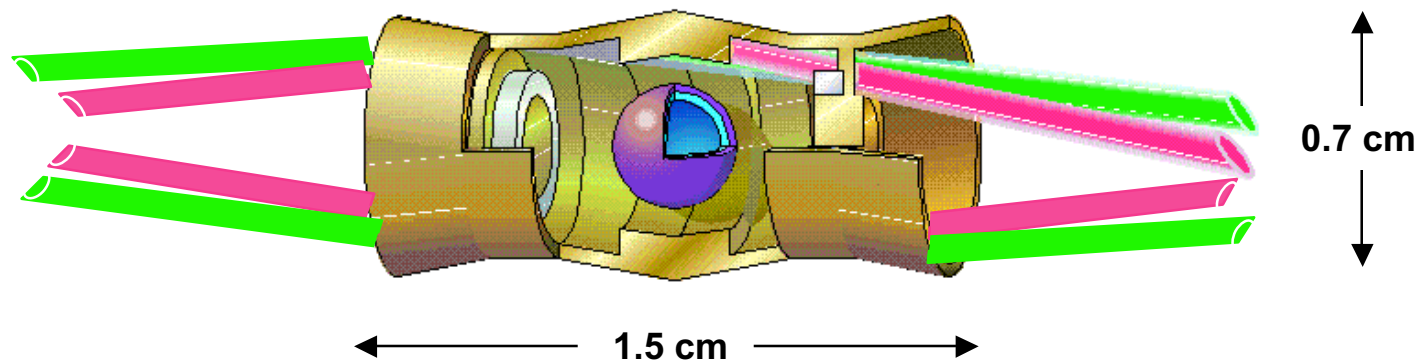
No CO₂ & no air pollution

Relatively short half-life for
components

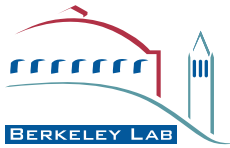


Heavy Ion Fusion Uses “Indirect Drive”

Ion Beams \Rightarrow *x-rays*
X-rays symmetrize in *hohlraum*



Requires *~ 500 Terawatts (!!)* (3 - 7 MJ in ~ 10 ns)
Ion Range \Rightarrow *1- 10 GeV*



Heavy Ion Accelerators are a Good Choice for a Fusion Driver

HEP / NP accelerators already have:

Long life

High pulse repetition rates

High electrical efficiency (~ 30%)

Present systems comparable to requirements in:

complexity

cost

ion energy



So why is it hard?

New Physics Regime for Accelerators

Target Requirements:

500 Terawatts

1- 10 GeV



For $A \sim 200 \rightarrow$

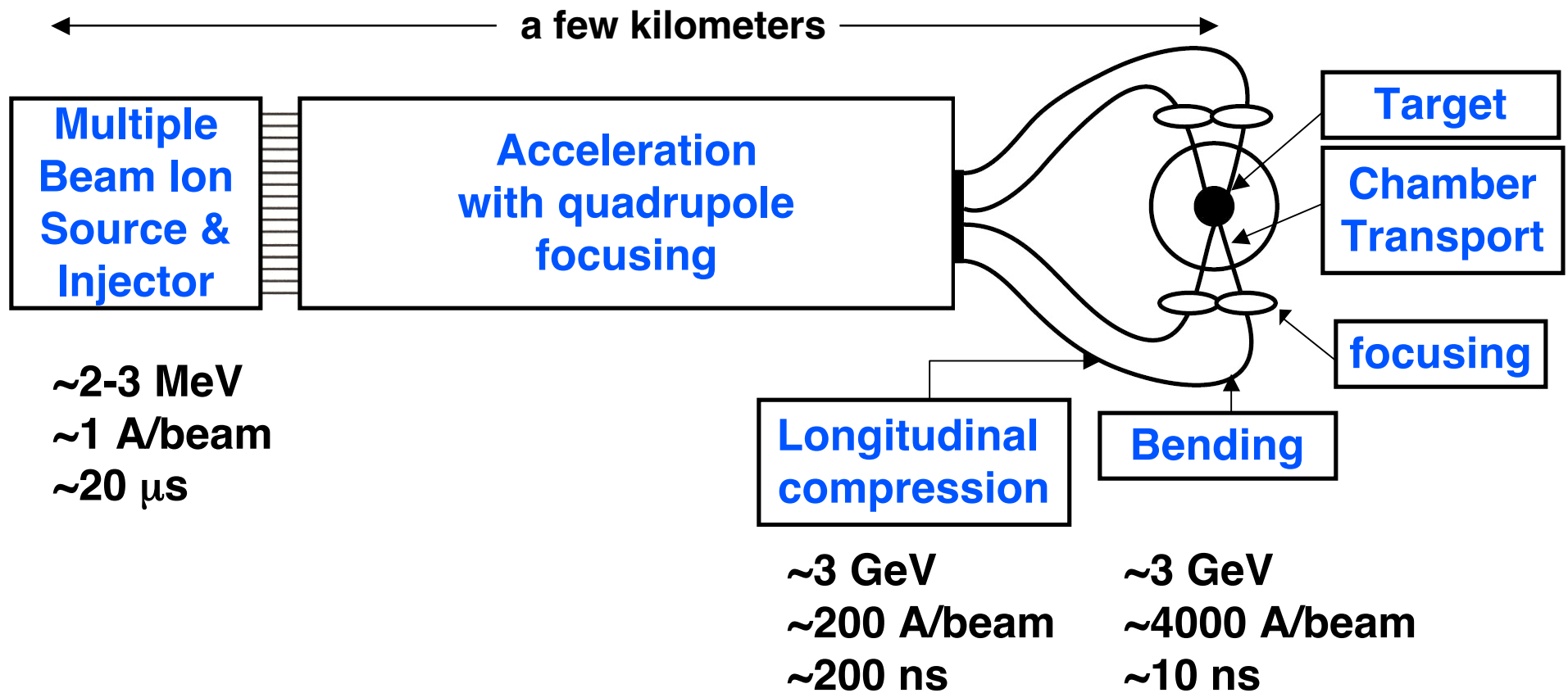
$\sim 10^{16}$ ions

~ 100 beams

Beam particles interact-- this dominates the physics.

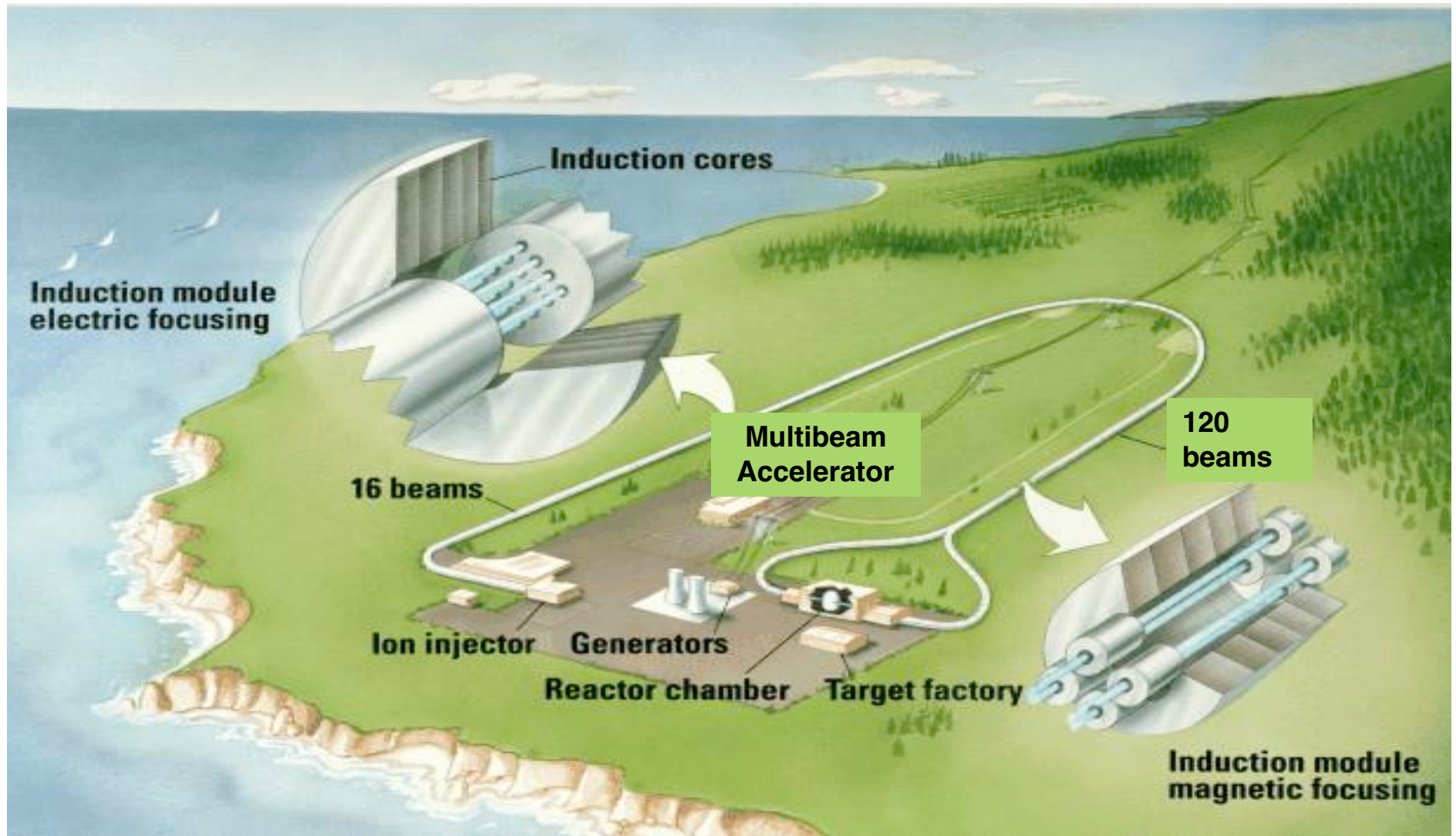


Schematic of a Heavy Ion Fusion Driver





An Artist's Conception of a Heavy Ion Fusion Power Plant





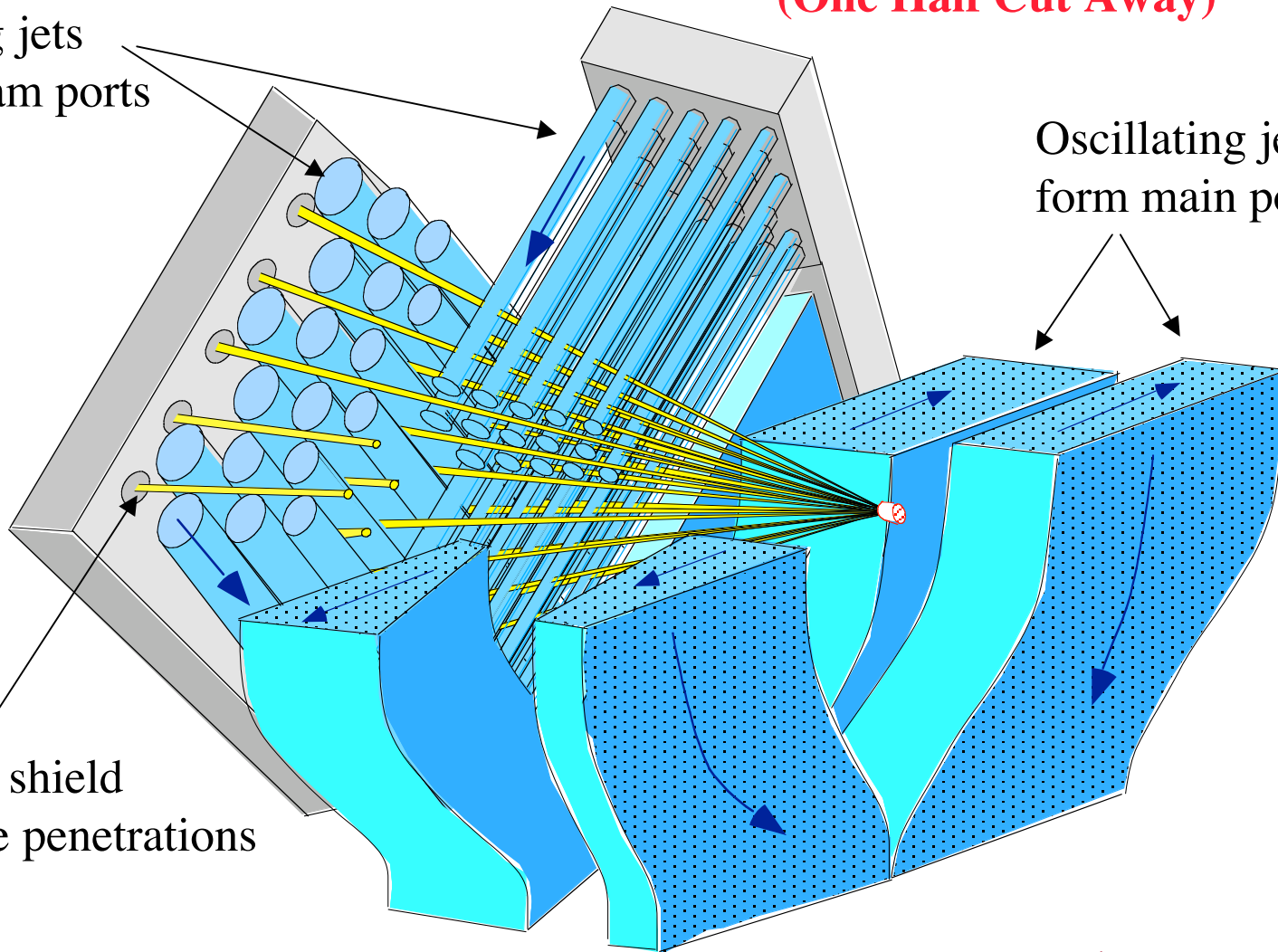
The First Wall is Protected by Neutron-thick Molten Salt (FLiBe)

(One Half Cut Away)

Crossing jets
form beam ports

Oscillating jets
form main pocket

Vortices shield
beamline penetrations





The Physics is almost all classical-- but it isn't simple!

$v/c \leq 0.2 \Rightarrow$ Maxwell + Newton is enough

But:

Particle interactions \Rightarrow Nonlinear forces

Nonlinear external forces:

focusing field errors

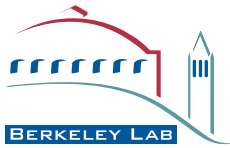
image forces from beam pipe wall

magnet fringe field forces

electrons

interactions with other beams

\Rightarrow Beam Heating, Waves, Instabilities



Particle-in-Cell Simulation Codes are Needed for Self-Consistent Calculations

For \sim **60,000 - 1,000,000 particles**:

Calculate forces on each particle

$$\vec{F} = q(\vec{E}_{\text{quad}} + \vec{E}_{\text{particles}})$$

Move Particles

$$\Delta \vec{x} = \vec{v} \Delta t$$

PIC Algorithm

Calculate new velocities after timestep Δt

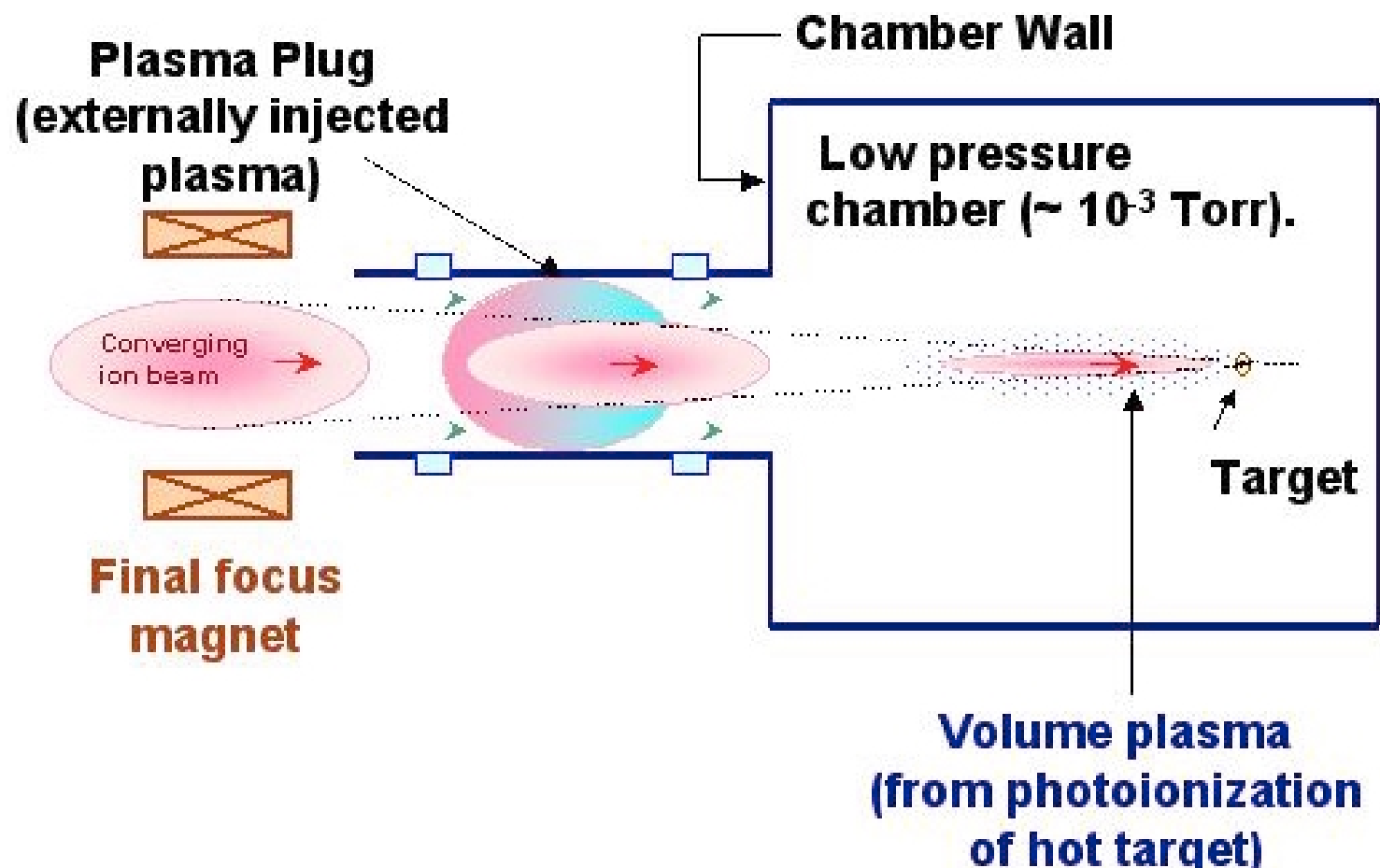
$$\vec{F} = m \vec{a}$$

$$\frac{\Delta \vec{v}}{\Delta t} = \frac{\vec{E}}{m}$$

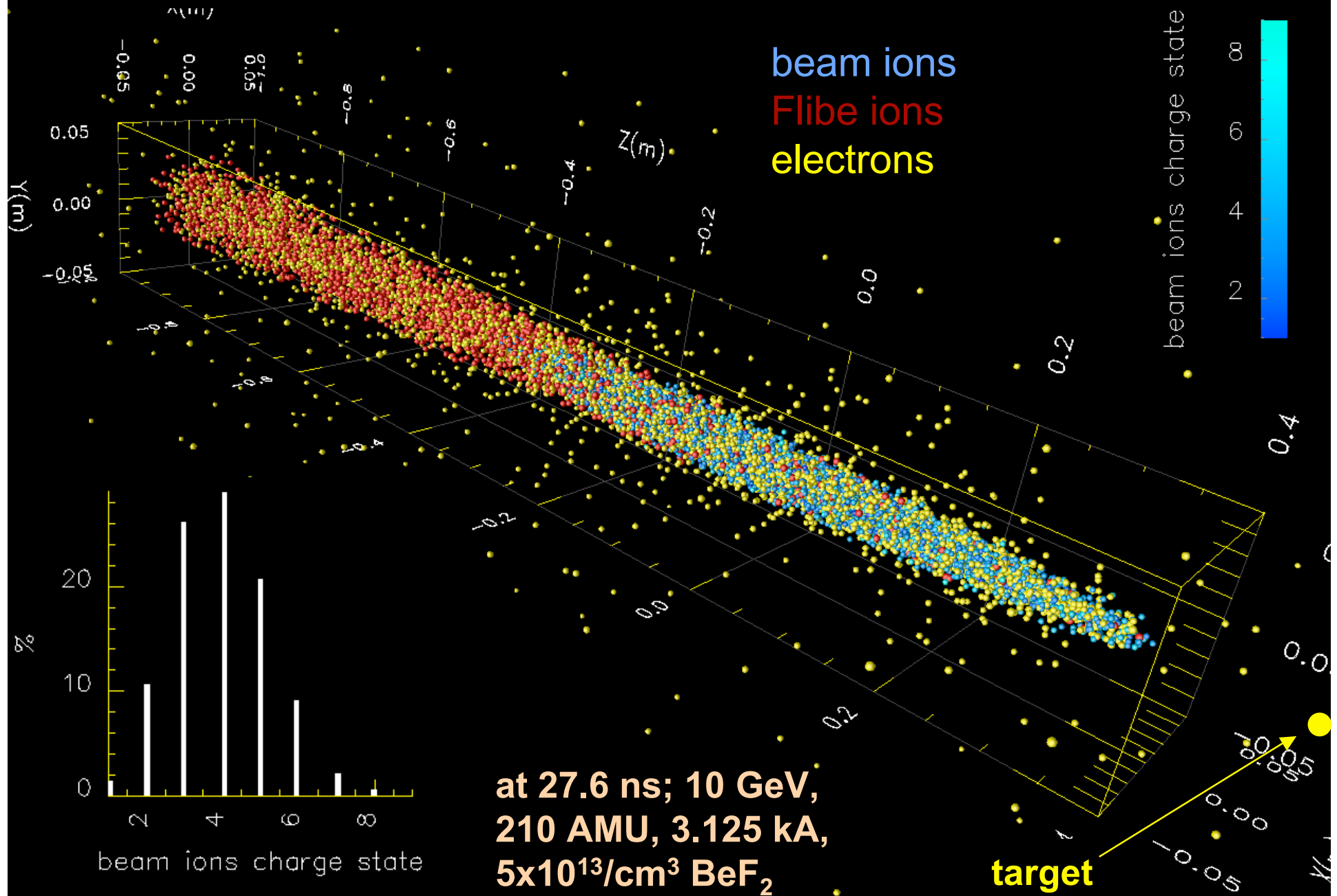
64 processors, 10 hours \Rightarrow
x ~ 300

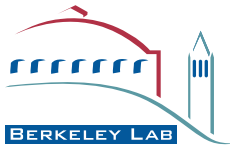


Neutralization competes with stripping in the target chamber



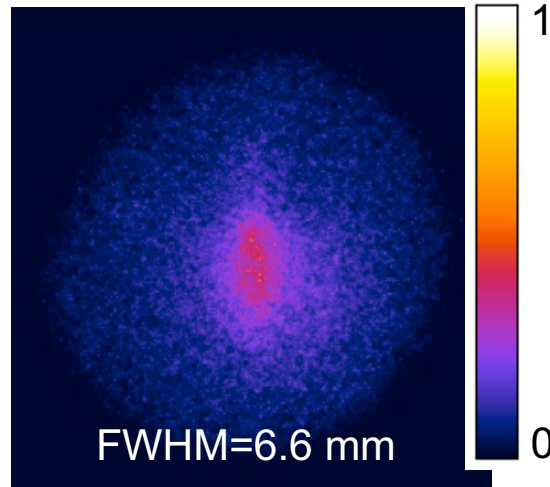
3-D BPIC simulation of beam propagating through Flibe



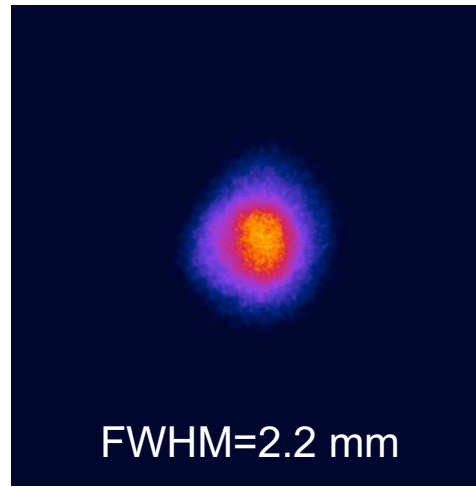


Reduction of spot size using plasma plug and volume plasma

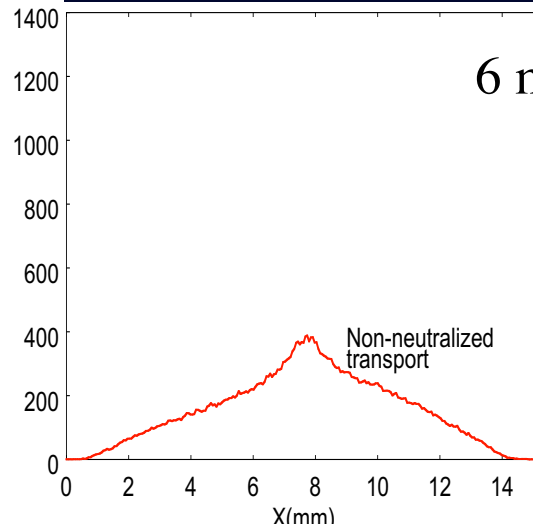
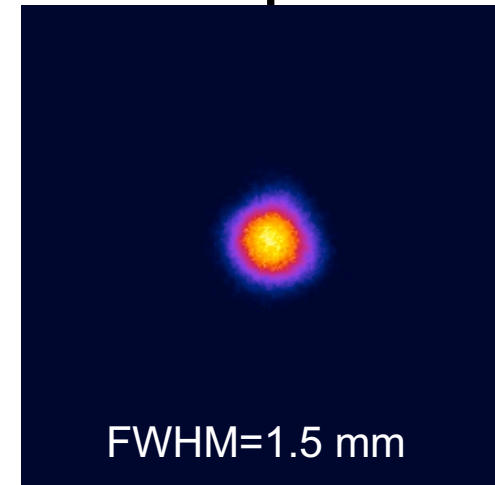
Non-neutralized



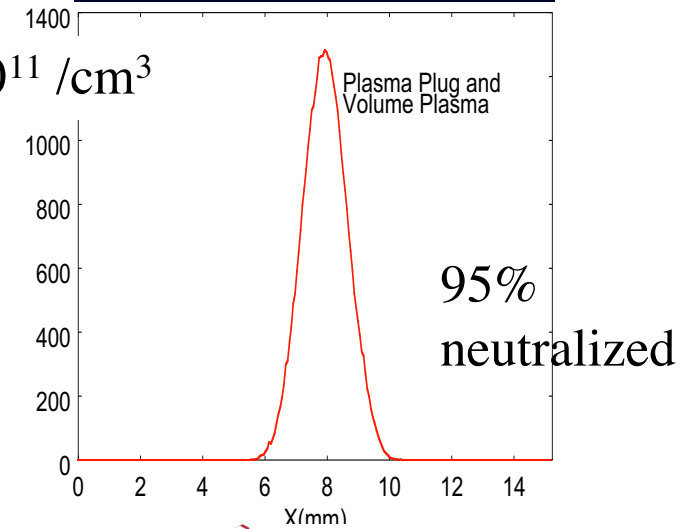
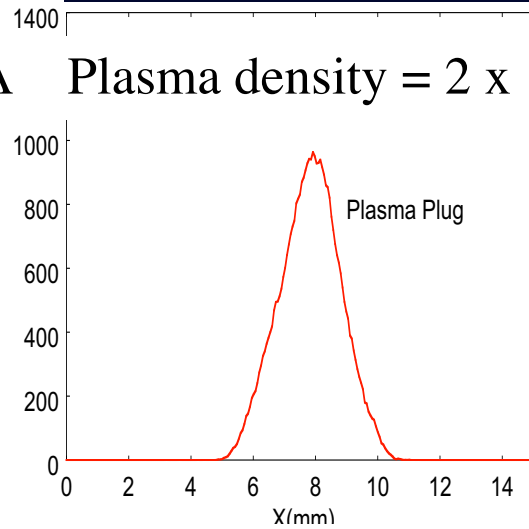
Plasma plug



Plasma plug & Volume plasma



6 mA Plasma density = $2 \times 10^{11} / \text{cm}^3$



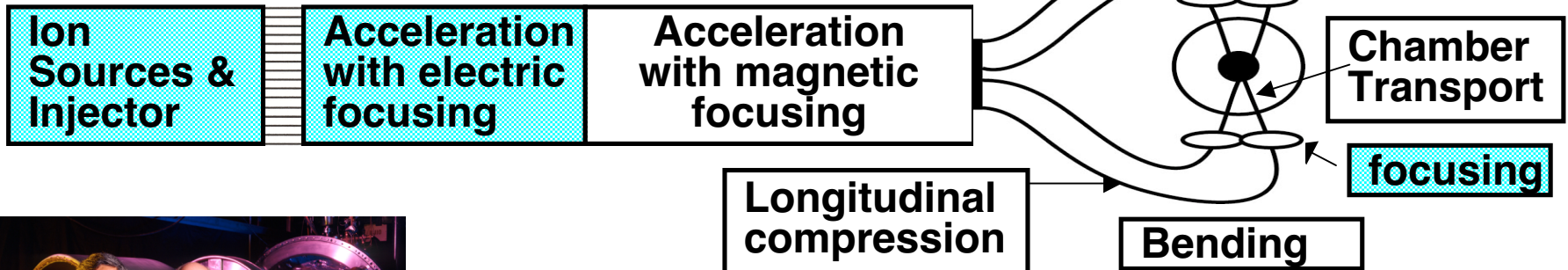


Accomplishments of Past HIF Experiments

Single Beam Transport Experiment



Multiple Beam Expt

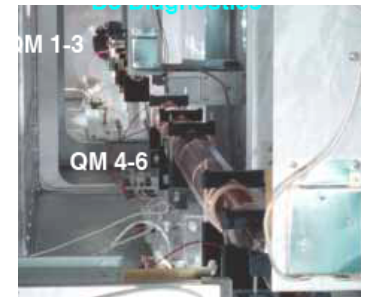


2-MeV Injector



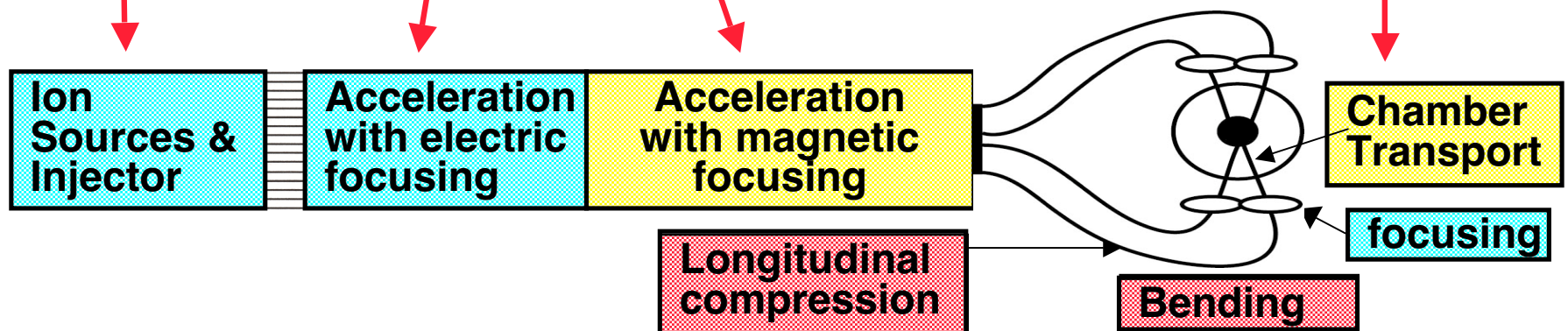
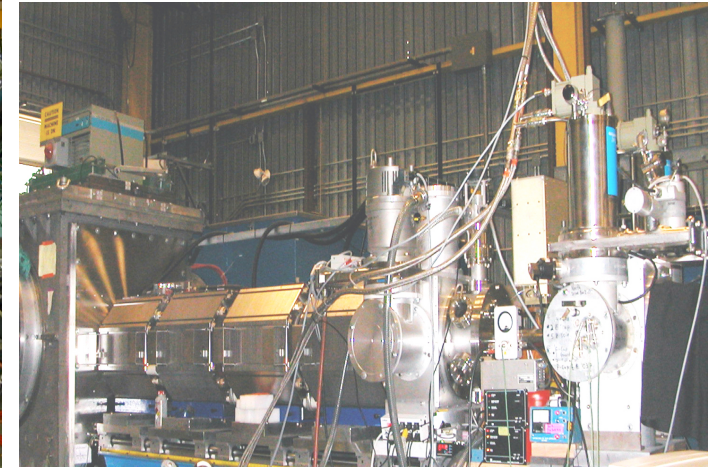
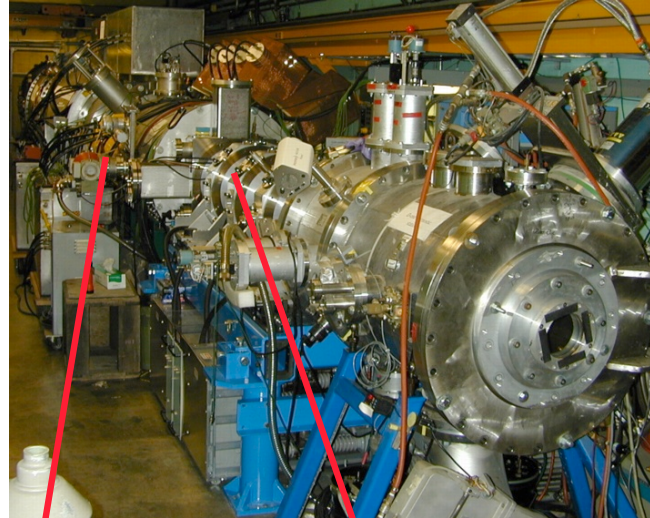
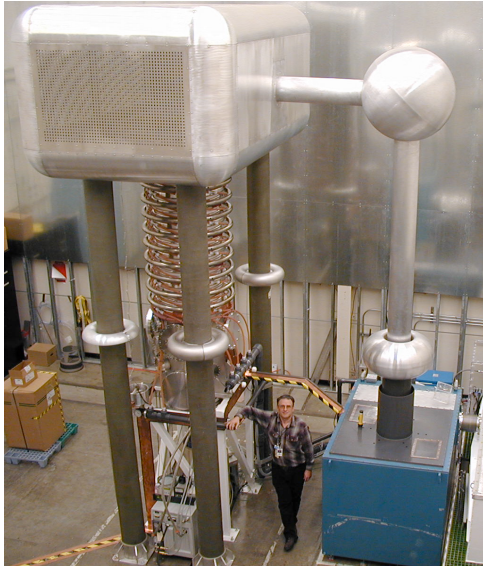
Beam Combiner

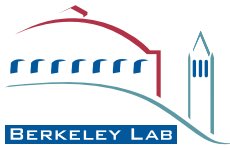
Scaled Final Focus



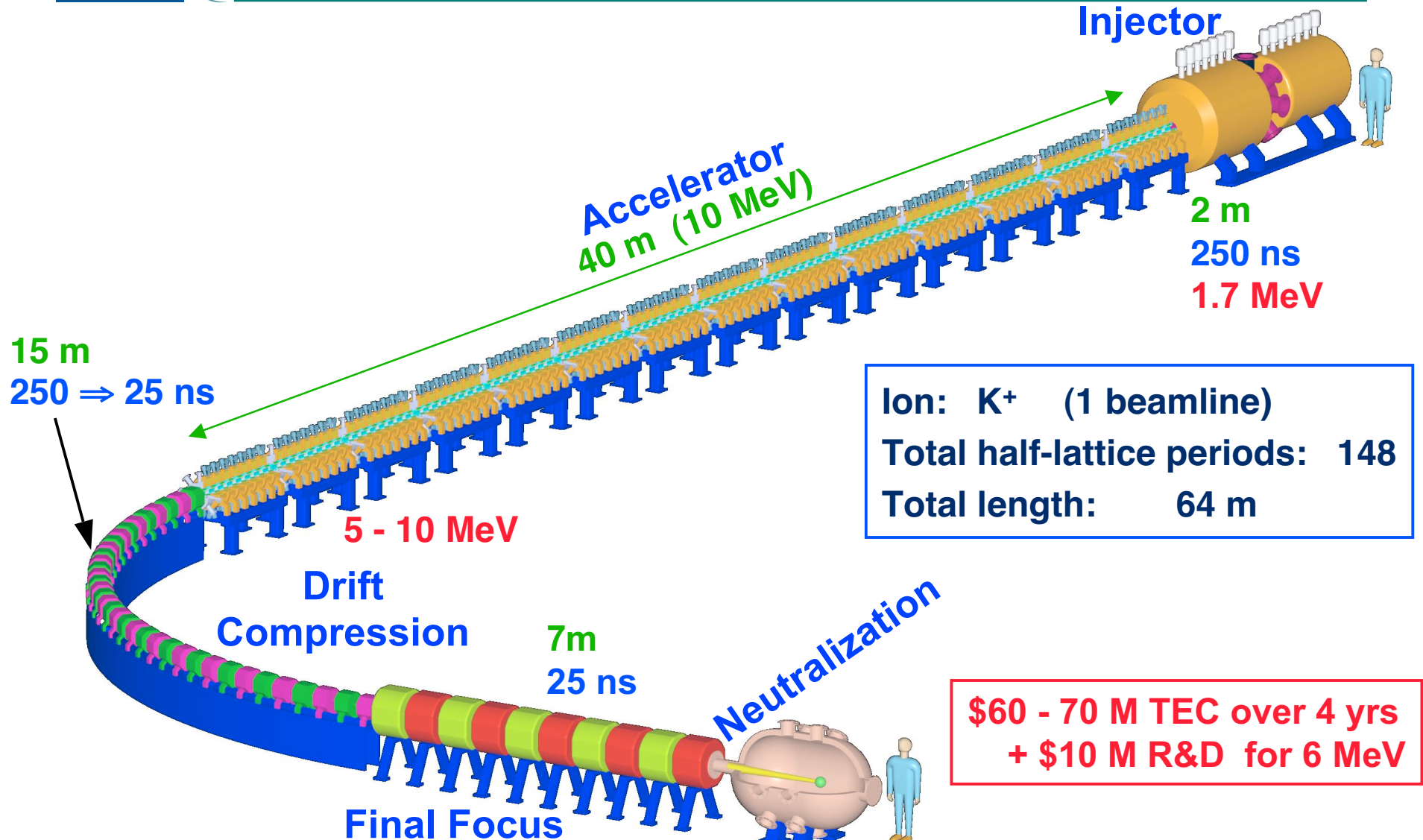


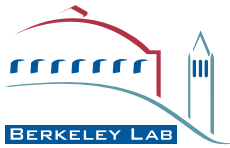
Current Experiments use Driver-Scale Beams





The IBX mission is to demonstrate integrated source-to-focus physics

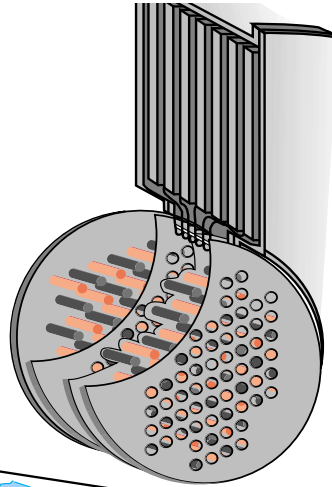




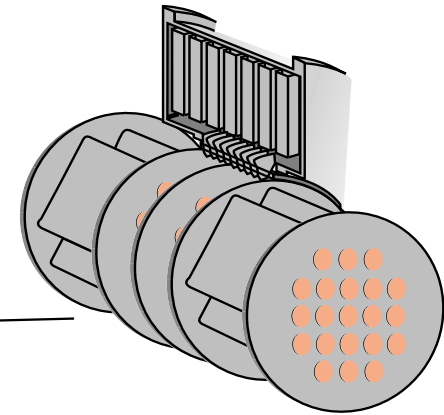
After IBX: The Integrated Research Experiment (IRE) will test all components & physics for an ETF

400 - 800 MeV
~ 30-200 kJ on target
~ 300 - 500 m
~ \$150 - 300 M

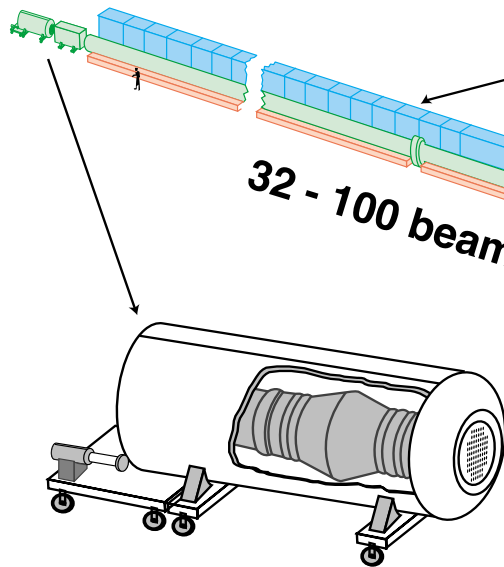
Acceleration &
Electrostatic Focusing



Acceleration &
Magnetic Transport

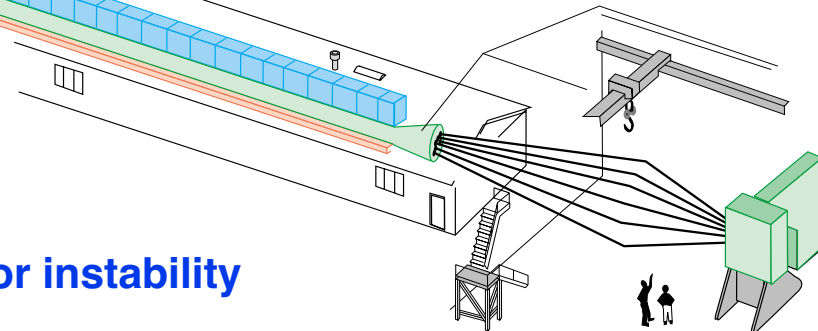


32 - 100 beams



Injector Source

Target physics:
Rayleigh-Taylor instability
 dE/dx



Target Chamber



Heavy Ion Fusion -- Peaceful Power for the Poor

